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Developing Mist-Annular Flow of R134a/PAG46 Oil in Inclined Tube at Compressor Discharge

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ABSTRACT

This work reports on the droplet flow rate and film thickness of a mist-annular flow inside inclined tubes in a mobile air conditioning compressor discharge. A preliminary model of single droplet trajectories was used to evaluate the potential for droplet deposition enhancement and it was found that it would be able to collect droplets with diameters of 25µm or higher at the inclined tube wall. A test section with a 1m long, 6.35mm i.d., transparent PFA tube was placed immediately after the compressor discharge in a full system facility. Tests were performed varying mass flux, oil circulation ratio (OCR), and inclination angles. For several positions in the tube downstream of the compressor, high speed video analysis was used to determine droplet sizes and velocities, and film wavelength in addition to an indirect indication of film thickness. The experimental trends obtained for droplet flow and film thickness for high mass fluxes, were the opposite of what was expected. There was an indication that the transition from horizontal to inclined orientation introduced disturbances in the film at the wall which caused the film to shed bigger droplets that were entrained back into the flow, increasing the drop flow rate in the inclined section. A small inclination angle (approximately 5°) neither enhances nor diminishes droplet deposition. Higher inclination angles, 11° and above, have a negative effect on the droplet deposition in the inclined section. At low OCR (0.43%), the presence of an inclined section did not affect the droplet deposition rate. At higher OCR (2.5%), a negative effect was observed in drop deposition.

1. INTRODUCTION

The presence of oil in air conditioning systems is necessary to reduce friction between moving parts and also to provide sealing between high and low pressure regions in the compressor. However, oil is not only found where it is primarily needed, instead it is carried over by the refrigerant vapor, leaving the compressor and circulating throughout the other components of the system. To characterize this oil carry-over, oil in circulation ratio (OCR) is often used ; this term is defined in Equation 1.

$$OCR = \frac{\dot{m}_{oil}}{\dot{m}_{oil}+\dot{m}_{ref}} \tag{1}$$

The additional flow of oil with the refrigerant has several detrimental effects on the performance of the air conditioning equipment. OCR causes a reduction in heat transfer coefficients on the refrigerant side (Kim et al., 2010, Pehlivanoglu et al, 2010). It also increases pressure drop in the heat exchangers and connecting lines (Pehlivanoglu et al., 2010;Kim et al., 2010). Another side effect of oil presence which is still not well understood is that it can worsen refrigerant distribution in evaporators, causing cooling capacity reduction of the system. A general rule seen in several works including DeAngelis and Hrnjak (2005), there is a 1% decrease in the coefficient of performance (COP) of the system for 1% increase in OCR. Mobile air conditioning systems usually operate with OCR ranging from 1% to 5%. Therefore, there is room for improvement in the performance by using better oil management strategies. Such strategies should focus on confining the oil to a very small region around the compressor, meaning that oil should be separated from the refrigerant vapor and returned to the compressor as soon as possible. Conventional techniques employ oil separators (gravitational, cyclonic, etc.), but these components impose high pressure drop or require large volumes in order to achieve high separation efficiency. The location right after the compressor provides the most ideal location for oil separation from the system perspective due to the very high apparent superheat, the amount of refrigerant dissolved in the oil is the lowest throughout the whole system. Separating the oil at this location causes the least impact on cooling capacity by reduction of refrigerant flow.

According to Wujek (2011), the flow leaving the compressor is of annular-mist nature, with the flow of liquid mainly in the form of droplets. He was able to determine droplet size and velocity distribution functions, as well as film thickness of the liquid annulus using optical techniques combined with high speed video and advanced image processing. Droplet sizes ranged from 10μm to 150μm over a wide range of mass fluxes (200 to 700 $kg/m^2.s$) and OCRs (1 to 20%). From these results it is possible to gage the difficulty that goes into balancing the trade-offs between pressure drop, volume, and separation efficiency with such a wide range of droplet diameters and such a complex flow regime.

This work stems out from the assumption that it would be easier to separate a relatively well behaved film on the wall than to try to design a compact separator that would be effective over the whole range of droplet sizes with low penalty in pressure drop.

2. BACKGROUND

Wujek (2011) studied the developing mist-annular flow coming out of a compressor using R134a/PAG46 oil mixture. The compressor was running in a full system facility and discharged in a 3m long 6.35mm i.d. transparent PFA tube. Using high-speed video and optical techniques, it was possible to determine how the liquid flow rate in the form of drops and film behaved along the length of the tube. The main finding of the work was that at the beginning of the tube, droplets deposit at a higher rate, causing the liquid mass flow rate in drops to decrease and the film thickness to increase to accommodate the deposited droplets. However, because the film gets thicker, instabilities at the vapor-liquid interface start to grow and eventually new, smaller droplets entrain back into the core flow. As one travels down the tube, an equilibrium drop flow rate is approached. This happens when the rate of droplet deposition equals the rate of droplet entrainment.

The result is reproduced in figure 1 and the trend just mentioned is observed. It is worth to note that summing up the fully developed drop flow and film flow rates one can very closely achieve the total liquid flow rate when using the measured OCR to calculate it. However, inside the developing region the agreement is not quite as good. The question remains on how to use this finding for the purpose of separating the oil/liquid mixture from the refrigerant vapor stream. As it was seen, even after several hundred diameters in tube length, there is still a significant amount of liquid flow rate entrained in the core flow as droplets. To make matters worse, Wujek (2011) showed that, as the flow progresses down the tube, the droplet size distribution becomes broader and it actually shifts to smaller sizes making it more difficult to separate.

Therefore this work investigates one of the possible ways to enhance droplet deposition in the discharge line, with little to no added volume and negligible added pressure drop. This is done by trying to take advantage of the axial momentum of the droplets and drive them to collide with the film by inclining the tube after a short straight horizontal section.

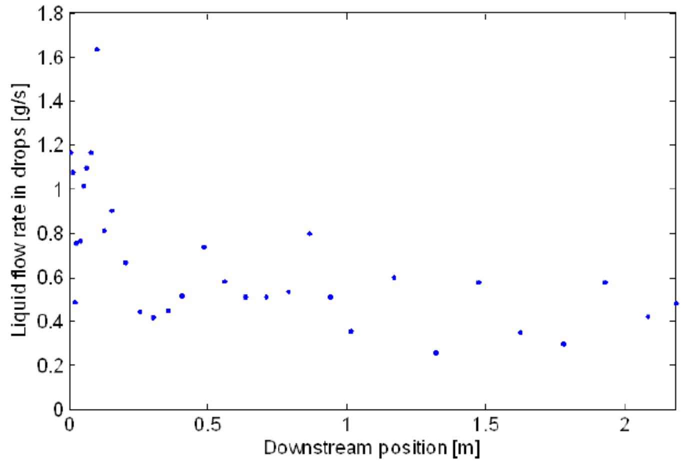


Figure 1: Droplet flow in straight tube from Wujek (2011).

3. METHODS

3.1 Preliminary analysis

As a merit evaluation exercise, a simplified model of a single droplet in a vapor flow bound by tube walls was developed. The model was used to determine which droplet sizes would have enough inertia, after a horizontal tube section, to collide with the tube wall and not follow the core flow change in direction. A free body diagram shown in Figure 2 was used to determine the droplet dynamics. The drag force was assumed to be an average force and the drag coefficient was determined from Equations 2 through 5 (Clift and Gauvin, 1970). Equations of motion are omitted from this paper due to its simplicity. The authors acknowledge the simplicity of this model and that small droplets will move in a somewhat random manner due to velocity fluctuations caused by turbulence. However, the objective is to have a rough estimate of the droplet trajectories to enlighten the reader of the motivation of the experimental work.

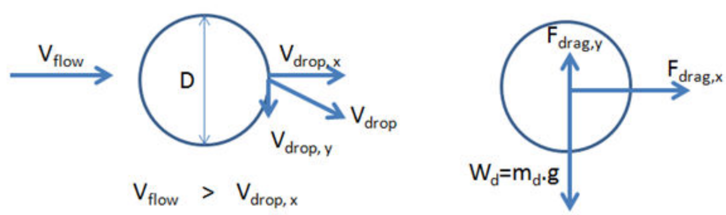


Figure 2: Droplet dynamics and force balance schematic.

$$F_{Drag,i} = C_D.\frac{1}{2}.\rho_v.\left(V_{flow,i} - V_i\right).\left|V_{flow,i} - V_i\right| \tag{2}$$

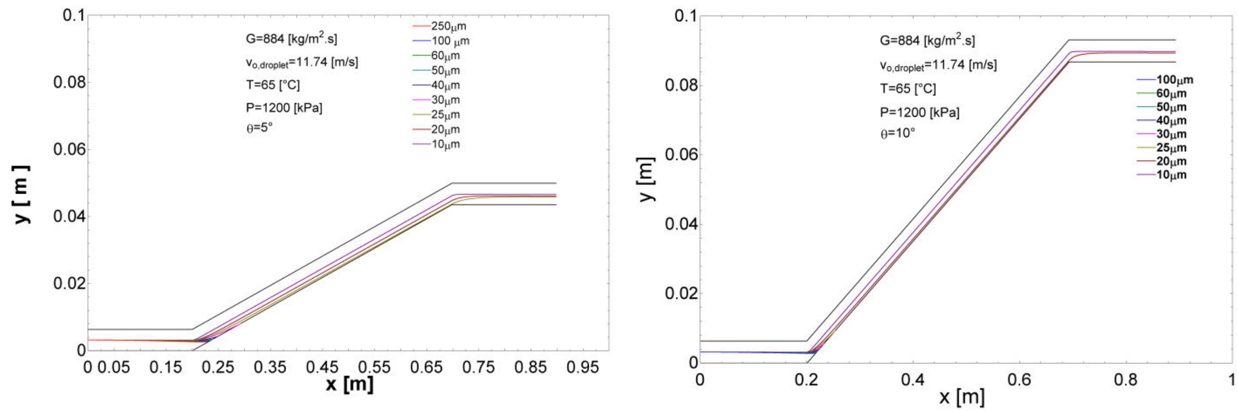
$$C_D = f.\frac{24}{Re} \tag{3}$$

$$f = 1 + 0.15.Re_r^{0.687} + 0.0175.Re_r.\left(1 + 42500.Re_r^{-1.16}\right)^{-1} \tag{4}$$

$$Re_r = \frac{\left|V_{flow,i} - V_i\right|.D_{drop}}{\nu_v} \tag{5}$$

The results for droplet trajectory are shown on Figure 3 . It was found that for the lowest inclination angle, 5°, the smallest droplet to collide with the tube wall was 30μm for a mass flux of 884kg/m^2-s and typical discharge conditions as stated on Figure 3. For an angle of 10° the smallest droplet to collide was 25μm in diameter. The size seems rather high given that sizes as small as 10μm are seen in the distributions presented by Wujek (2011).

However, analyzing the cumulative mass distribution function from his data, one can find that more than 80% of the mass is present in droplets bigger than 30μm. This is a very encouraging finding in a preliminary modeling stage. Therefore it is worth moving forward into experimental exploration of the problem.

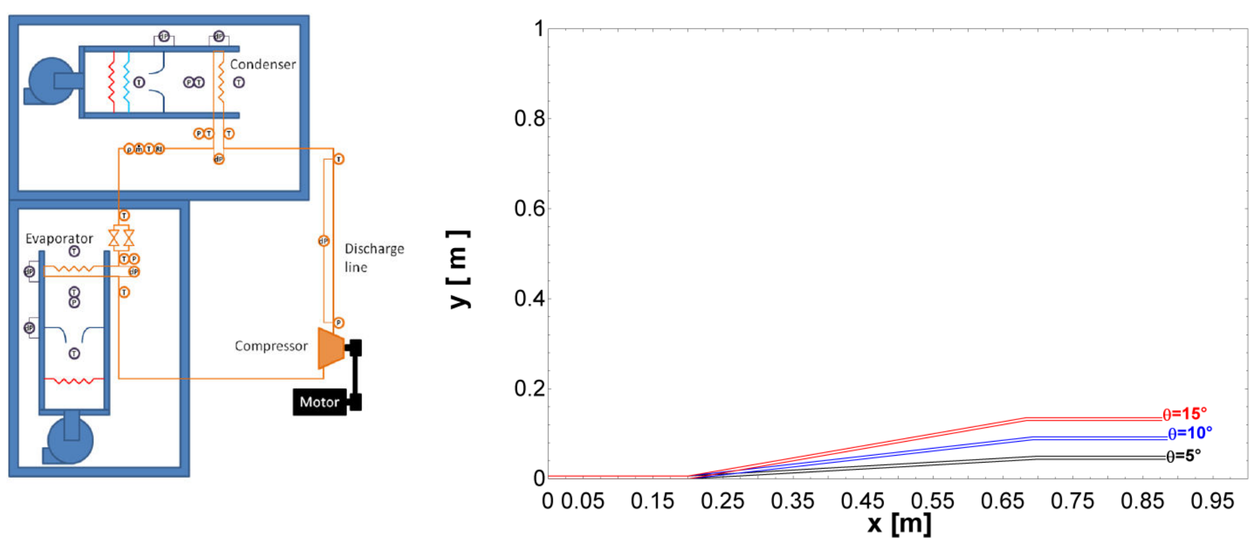


(a) (b)

Figure 3. Single droplet trajectory for various droplet sizes in a (a) 5°, and a (b) 10° inclined tube.

3.2 Experimental facility and techniques

Figure 4 shows a schematic of the experimental facility. The compressor is operated in a full system facility. The refrigerant/oil pair used is R134a/PAG46. The discharge port is connected to a 3m long, 6.35mm i.d. tube. The tube is laid out in a way that immediately leaving the compressor there is a 0.2m long horizontal straight section, after that the tube is inclined at the desired angle for another 0.45m and then straightened out for another 0.2m. Figure 5(b) shows the aspect ratio of the test section for various inclination angles. High speed videos for droplet size, velocity, and film thickness determination are taken along the length of the tube at 9 different positions. Tests were performed with various OCRs, tube inclination angles, and mass fluxes. The effect of each of these variables was studied independently. A total of 8 operating conditions were investigated, generating close to 72 data points. Table 1 shows a matrix of measured conditions.



(a) (b)

Figure 5: (a)Schematic of the experimental facility (Wujek, 2011); (b) test section aspect ratio;

Table 1: Test matrix

Variable	Effect of Mass flux			Effect of OCR		Effect of Angle		
G [kg/m^2.s]	189	524	678	568	524	562	524	562
OCR[%]	2.1	2.52	2.8	0.43	2.52	2.5	2.52	2.5
Angle [°]	16.41	16.41	16.41	16.41	16.41	5.50	16.41	11.07

During the tests, pressure, temperature and mass flow rates were recorded. In order to determine OCR, a sampling methodology in compliance with ASHRAE Standard 41.4 (1996) standard procedures was employed.

Droplet size and velocity distribution were determined using the same techniques and in-house software developed by Wujek (2011) and Wujek and Hrnjak (2010). On a brief note, the software for droplet size and velocity deals with the image by removing the wavy features of the slow moving film at the wall and focusing on the droplets behind it. This is done by first subtracting an average of all the frames in the video and then shifting each frame by a certain distance corresponding to the speed of the waves in the film, and subtracting each frame so that it removes the wavy features. The droplet flow rate is determined according to the methods presented in Wujek (2011) by multiplying the droplet concentration by the vapor flow rate. It was shown by Ambrosini et al. (1991) that the film thickness correlates linearly with the film wavelength. The thicker the film the longer the wavelengths are. Therefore, a qualitative film thickness comparison will be made based on the film wavelength values. Example results that can be extracted from the videos are shown on Figure 6.

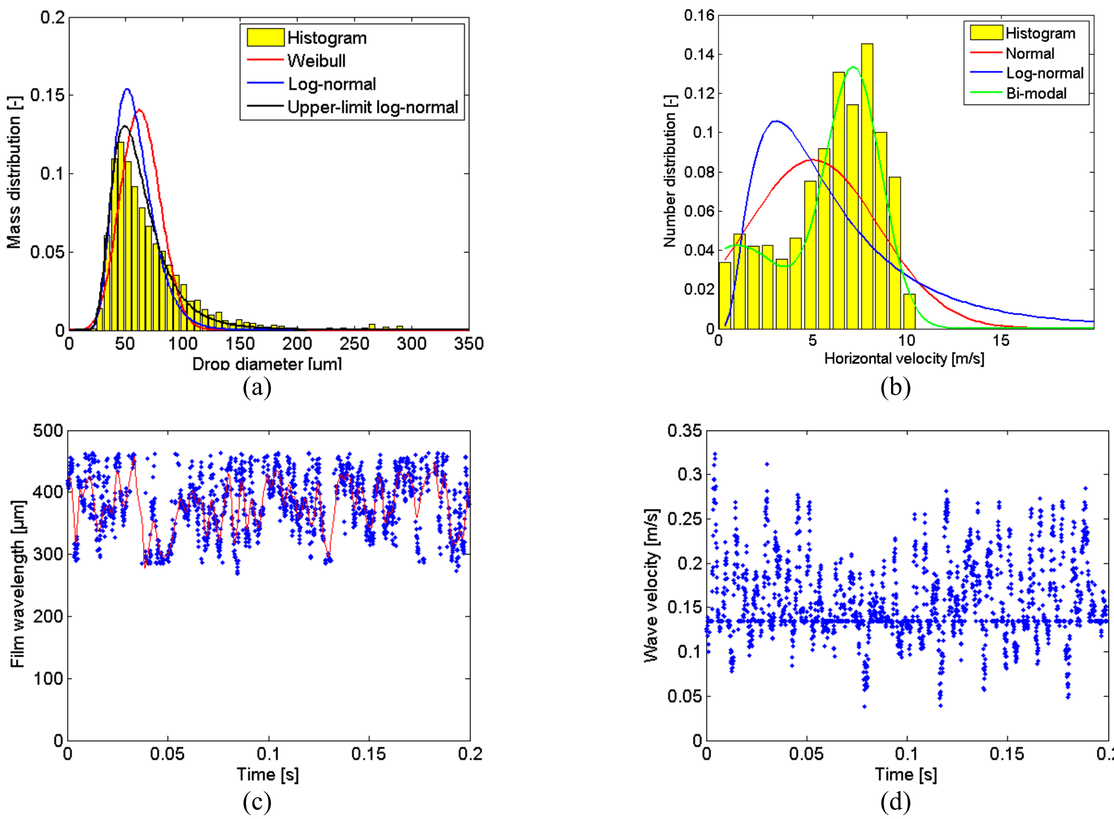


Figure 6: Example results that can be extracted from the videos with the in-house processing software; (a) Droplet size distribution; (b) droplet velocity distribution; (c) film wavelength; (d) film speed; G=524kg/m^2.s, 16.41°.

4. RESULTS AND DISCUSSION

As the objective of this work is to investigate if droplet deposition can be enhanced by placing an obstacle, in this case the tube wall, in the droplet flow path, nothing is more natural than to present the results in the form of droplet mass flow rate versus tube length.

It is interesting to first establish the expected result for droplet flow rate and film thickness or film wavelength. It is intuitive that, given the film changes direction undisturbed when the tube is inclined, the droplet flow rate and film thickness will present a behavior like that shown on Figure 7. The proposed or expected behavior is based on the observations that the drop flow rate will drop sharply at the beginning of the tube, and on the preliminary modeling results showing that droplets that have enough inertia will collide with the tube walls, therefore increasing the droplet deposition rate and film thickness.

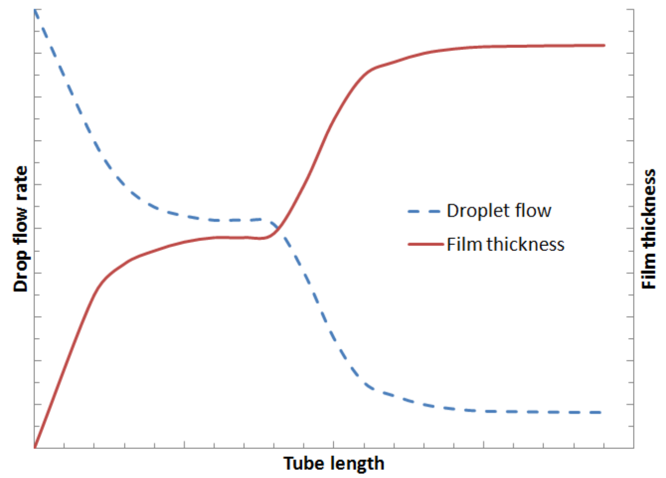
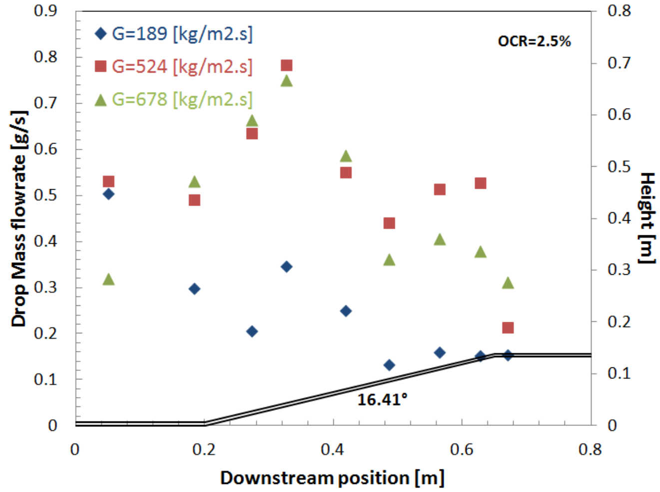


Figure 7: Expected trend for droplet mass flow rate and film thickness.

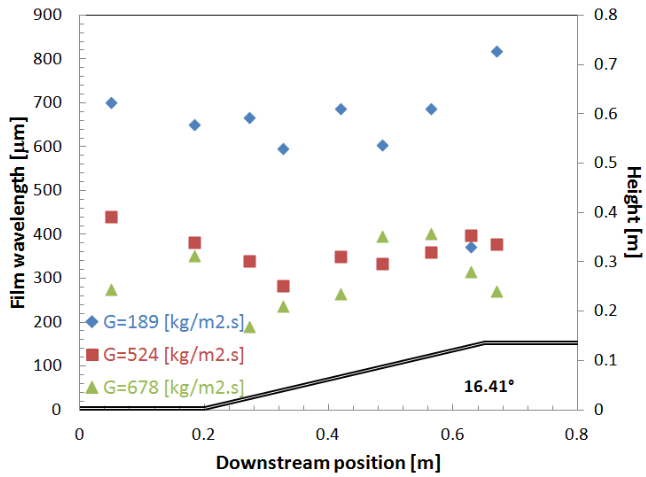
Figure 8 shows droplet mass flow rate and film wavelength development along the tube for three different values of mass flux, at a constant OCR and inclination angle. It is noticeable the difference between the idealized trend of Figure 7 and the results shown here. The trend can be somewhat generalized for higher mass fluxes that after the flow turns into the inclined section, drop flow rate increases up to a certain value and then starts do decrease again reaching a minimum and even starting to go up once more before the inclined section is made horizontal again. For lower mass fluxes the trend resembles the one observed for horizontal tubes by Wujek (2011).

The somewhat undesired trend for higher mass fluxes can be explained with the help of figures 8(b) and 9. Figure 8(b) shows that film wavelength, which is directly proportional to film thickness, presents the opposite trend of the drop mass flow, granted some measurement uncertainty. This is expected, and was anticipated in Figure 7. What is interesting is the observation that can be made from Figure 9, where the volume based mean droplet diameter is plotted against tube length. It is clear that right after the tube is inclined, there is a shift in the mean diameter towards bigger droplets. If the tube continued to be horizontal, the shift would be to smaller sized droplets as observed by Wujek (2011), and that shift in distribution was explained by accounting for new droplets being entrained off the film by being ripped off the crests of disturbance waves. The presence of new, bigger droplets after the turn in the tube indicates that an external disturbance was induced in the film by the geometry of the turn and that caused the drop flow rate to increase. Towards the end of the inclined section, droplet mean diameters either stay the same or decrease, indicating that re-entrainment is occurring at a higher rate than deposition, causing the drop flow rate to increase. This is again an undesired effect.

The scope of this work was limited to inclination angles up to around 15° in order to keep film disturbance to a minimum to avoid triggering droplet re-entrainment too soon. However, the results shown for 16.41° show that at the vicinity of the point where the tube is inclined, droplet flow rate increases very sharply for higher mass fluxes, with the increase being smaller or even negligible for low mass fluxes. Figure 10 shows the droplet flow rate and film wavelength results for three inclination angles, with OCR and mass flux being kept almost constant. The trend seen is that for angles of 11.07° and 16.41° the shape of the curves is similar to when varying mass flux and can again be explained by the same arguments used previously with the aid of Figures 10(b) and 11. For the smaller angle, 5.5°, the drop flow rate remains practically unchanged until the flow reaches past half of the inclined length, where it drops sharply and then starts re-entraining and increasing droplet flow rate.



(a)



(b)

Figure 8: effect of mass flux on (a) droplet flow rate and (b) film wavelength.

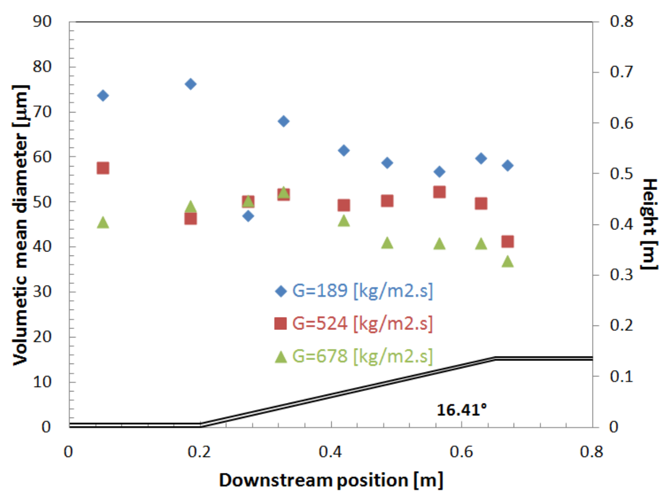
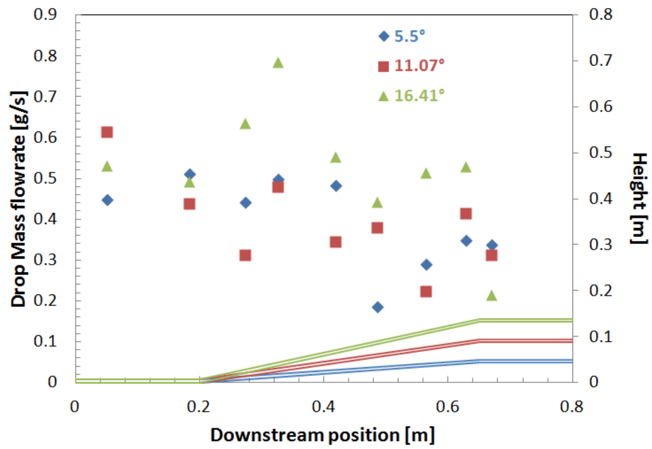
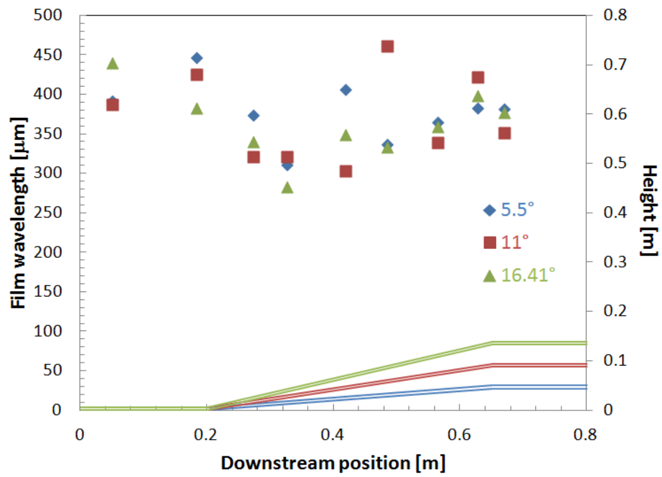


Figure 9: Change in volumetric mean diameter as the flow progresses down the tube as a function of mass flux.



(a)



(b)

Figure 10: Effect of inclination angle on droplet flow rate and film wavelength.

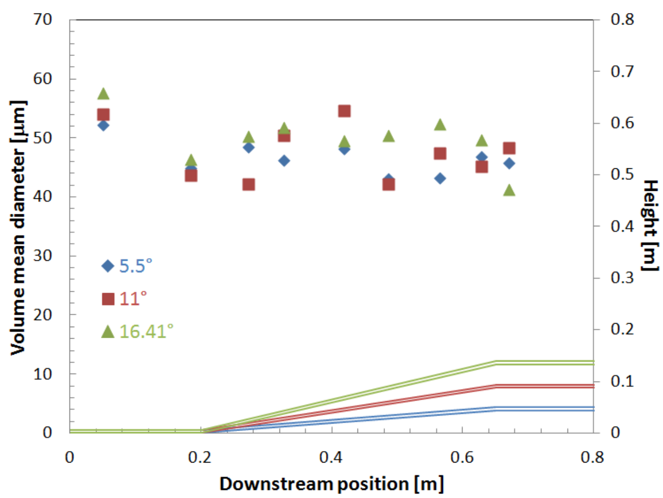


Figure 11: Change in volumetric mean diameter as the flow progresses down the tube as a function of angle.

In addition to inclination angle and mass flux, two different OCRs were tested, 0.43% and around 2.52% at similar mass fluxes (568 and 524kg/m^2.s) and inclination angle (16.41°). Figure 12 shows that for low OCR the drop flow rate is practically unaffected by the presence of the inclined section, following a behavior very close to that of a developing flow in a horizontal tube. This can be explained by looking at the wall flow regimes in the two situations. For an OCR of 2.5% the tube wall is completely wetted and a film is flowing. For the low OCR the wall flow regime oscillates between completely wetted (wavy film) and partially wetted (rivulets or drops). Figure 13 shows three frames of video which characterize the flow regime at the wall. In the low OCR case, the flow goes by the change in direction without too much disturbance of the liquid that is flowing at the wall, even when the wall is completely wet, due to low liquid velocity.

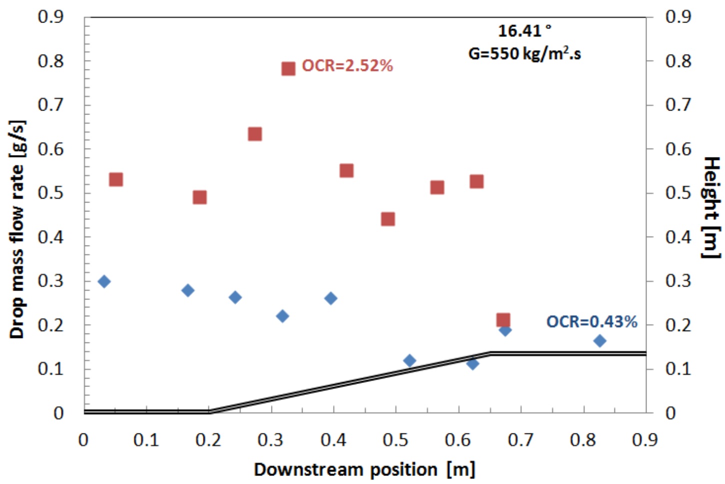
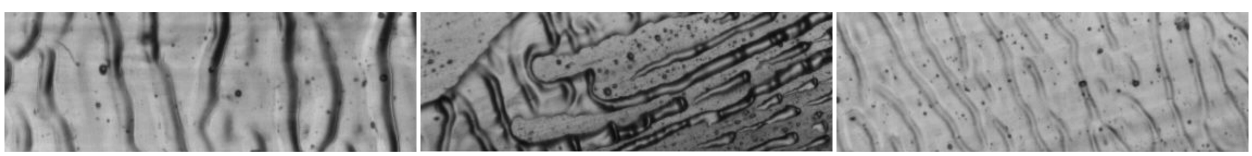


Figure 12: effect of OCR on droplet flow rate.



(a) (b) (c)

Figure 13: Flow regimes for (a) OCR=2.5%, fully wet; (b) OCR=0.43%, partially wet; (c) OCR=0.43%, fully wet.

5. CONCLUSIONS

Even though physically intuitive observations from previous works and simplified models showed encouraging results, an initial experimental investigation of droplet deposition enhanced by means of an inclined section in a tube, proved the phenomena is far more complex and deserves further attention. The transition from horizontal to inclined tube sections introduced external instabilities to the film flowing at the wall at higher mass fluxes and generated new, bigger droplets that were entrained in the core flow causing the drop flow rate to increase instead of the desired decrease.

For small inclination angles, the flow passes by the transition with negligible disturbance and in fact, the drop flow rate drops sharply just past the middle of the test section, this suggests that there might be an optimum angle and inclined section length that can be advantageously used to enhance liquid separation from the core flow. For low OCRs, the inclined section has little effect on the flow, therefore the drop flow rate reduction continues at the same pace as in the horizontal section.

More work is needed to better understand how to avoid film disturbances in the transition from horizontal do inclined section. This includes visualization of the flow at the turn to indentify generation mechanisms of bigger droplets and subsequently methods to mitigate entrainment.

NOMENCLATURE

C	coefficient	(-)
D	diameter	(m)
F	force	(N)
f	multiplication factor	(-)
$\dot{m}$	mass flow rate	(g/s)
OCR	oil in circulation ratio	(-)
ρ	density	(kg/m^3)
Re	Reynolds number	(-)
V	velocity	(m/s)
ν	kinematic viscosity	(m^2/s)

Subscripts

drop	droplet
Drag	drag
flow	gas phase
i	x or y direction
r	relative
v	vapor

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